FINDINGS

OF THE

Moon→Mars SCIENCE LINKAGES SCIENCE STEERING GROUP (MMSL-SSG)

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Note: This is the presentation version of the white paper "Final Report of the Mars-Moon Science Linkages Science Steering Group (July, 2004)". If there are any discrepancies between the two documents, the white paper should be judged to be superior.

MMSL SSG Charter

The Moon→Mars Science Steering Group was chartered on behalf of MEPAG to complete the following:

1. Develop an analysis of the potential ways in which the scientific objectives for the exploration of Mars can be advanced through any of the following activities:
    a) Scientific investigations on the Moon
    b) Engineering demonstrations on the Moon (including demos of technically challenging scientific activities)
        - Demonstrations of instrument, tool, and spacecraft operations.
2. Develop an assessment of the priority of the possibilities outlined above.

Moon→Mars SSG Membership

Science Members		
Ariel Anbar	Univ. of Rochester	geochem of early earth, A/B
Bruce Banerdt	JPL	geophysics
Don Bogard	JSC	Geochronology
Bruce A. Campbell	Smithsonian CEPS	geophysics/SHARAD
Michael Duke	Colorado School of Mines	Resources
Lisa Gaddis	USGS, Flagstaff	remote sensing, MER
Brad Jolliff	Wash. U.	petrology/geochemistry
Rachel C. F. Lentz	U Tennessee	petrology/geochemistry
David McKay	JSC	geology/astrobiology
Greg Neumann	GSFC/MIT	Geophysics/geodesy
Dimitri Papanastassiou	JPL	geochem (isotopes)
Roger Phillips	Wash. U.	geophysics, geology
Jeff Plescia	JHU APL	Mars geology
Charles Shearer	U. New Mexico	petrology/geochemistry
Mini Wadhwa	Field Museum, Chicago	geochemistry, meteorites
Program Representatives		
David Beaty	MPO--JPL	Program manager
Jim Garvin	NASA HQ	Program Science

Bold denotes team leader

MMSSG subcommittees

•**Mars Priority sub-team**. Bruce Banerdt, Mini Wadhwa, Rachel Lentz.

•**Moon Priority sub-team**. Don Bogard, Dimitri Papanastassiou, Bruce Campbell

•**Overall Priority sub-team**. Roger Phillips--leader

Assumptions for this Study

1. Assume scientific priorities for the exploration of Mars are described in the MEPAG Goals document (http://mepag.jpl.nasa.gov/reports/MEPAG_goals-3-15-04-FINAL.doc).

2. Assume a Lunar Reconnaissance Orbiter (LRO) mission to the Moon in 2008, a robotic landed mission by 2010, and a TBD schedule of robotic lunar missions (perhaps on an annual basis?) until a first human return to the lunar surface in 2020.

3. This SSG is asked to focus its effort on martian and lunar surface science, rather than orbital science.

Assumptions for this Study

Lunar science objectives

The most recent consensus-based description of lunar science goals, objectives, and investigations was developed by the Lunar Exploration Science Working Group (LExSWG). This information is available in the following reports:

1. A Planetary Science Strategy for the Moon, Lunar Exploration Science Working Group, July 1992, JSC document JSC-25920, 26 pp.
2. Lunar Surface Exploration Strategy, Lunar Exploration Science Working Group (LExSWG), Final Report, February, 1995, 50 pp.
   Both available at: http://www.lpi.usra.edu/lunar_return/

The LExSWG position is assumed here. Integration with MEPAG goals is summarized below.

The Moon as a Unique Vantage Point for Solar System Exploration

<u>FINDING</u>: The Moon offers a unique vantage point for certain aspects of Solar System exploration

- Cornerstone for Early Planetary Processes
- Volatile Record and Reservoirs
- Testbed for Scientific Exploration of the Solar System
- Astrobiology

<u>Cornerstone for Early Planetary Processes</u>

- Preserves the remnants of one style of planetary differentiation: Magma Ocean.
- Illustrates a style of early planetary asymmetry that is related to early differentiation processes.
- Illustrates a pathway of planetary evolution that is related to a style of planetary accretion and differentiation.
- Illustrates the full crustal formational and magmatic history of a cooling planetary body.
- Recorded and preserved the early impact environment of the inner solar system.
- Interactions between a planetary surface and space are preserved in the lunar regolith.

The Moon as a Unique Vantage Point for Solar System Exploration

Volatile Record and Reservoirs

- Moon is an planetary end-member for volatile abundance.
- Three primary sources of volatiles:
  - Endogenous
    - Volcanism, volcanic degassing
  - Exogenous
    - Solar wind and galactic cosmic rays
    - Impacts of comets and asteroids
- Lunar surface contains all three, although endogenous volatiles are in very low abundance. The lunar surface is unprotected from space exposure.
- Lunar surface records solar wind, galactic cosmic ray history. Polar cold traps may record the more volatile species from volcanic eruptions and impacts.
- Martian surface contains abundant endogenous volatiles and is protected by atmosphere and potentially larger ancient magnetic field.
- Volatiles on Mars, especially water, present at poles, in megaregolith, in atmosphere, bound in minerals, etc.

The Moon as a Unique Vantage Point for Solar System Exploration

Testbed for Scientific Exploration of the Solar System

- The Moon has a number of unique testbed attributes:
  - Close proximity to Earth.
  - Hostile environment.
    - *Atmosphere*
    - *Temperature*
    - *Low volatile content*
    - *Dust*
  - Reduced gravity levels.
  - Low seismicity.
  - Planetary-scale sterile environment.

The Moon as a Unique Vantage Point for Solar System Exploration

Astrobiology

●The Moon preserves unique historical information about events and processes that affected the habitability of the entire inner Solar System, a record obscured on Earth and Mars.

- *Impact chronology (esp. first billion years)*
- *Composition of impactors, IDPs flux, etc.*
- *Delivery of exogenous volatiles and organics*
- *Nearby supernovae and Gamma Ray Burst (GRB) events*
- *Solar activity (solar wind; flares)*

●The Moon provides a uniquely accessible planetary-scale sterile environment useful for assessing engineering goals of astrobiological importance, especially for life detection and planetary protection.

- *Control experiments for life-detection technologies (extinct and extant)*
- *Quantify "forward contamination" by robotic and human explorers*

Moon→Mars Linkages

FINDING: We have identified three categories of linkages between possible lunar exploration activities and a future benefit to martian science. These are organized as:

- **Category A. Investigations related to processes of terrestrial planet formation and evolution**
- **Category B. Human-related resource issues**
- **Category C. Demonstrations of scientific methods and capabilities**

Category	# of Linkages Identified
A	10
B	3
C	7
TOTAL	20

Category A.

Investigations related to the processes of terrestrial planet formation and evolution (experienced by both Moon and Mars)

- The Moon provides an ancient record of the early evolution of the terrestrial planets that is partially to totally erased on Mars.
- Early evolution of the solar system - volatiles, comet abundance, solar history

A1. Interior Planetary Structure

What is the Linkage?

- Understanding the structure of planetary interiors is fundamental for understanding the origin and differentiation of a planet, dynamical processes, surface evolution, tectonics, magmatism, and magnetic field.

Relevance to Lunar Science

- Provide constraints for the bulk composition of the Moon, its origin, and the manner in which it differentiated.
- Characterize crust, mantle, core structural domains, to anchor our understanding of lunar asymmetry, mantle dynamics, magnetic field and current thermal state.

Relevance to Mars Science

- Place constraints on the mechanism of martian differentiation and early dynamical processes of the martian interior.
- Characterize the current structure and dynamics of the martian interior.
- Determine the origin and history of the magnetic field.

Possible Lunar Measurements

- Moon-wide seismic array.
- Far side gravity field measurements.
- Detailed topography measurements
- Ranging to Transponders on Surface

A2. Early Planetary Differentiation

What is the Linkage?

- Mars and the Moon both differentiated. A complete understanding of the general process will benefit from observations at both places.
- Different products of differentiation are preserved and exposed on the two bodies.

Relevance to Lunar Science

- Mechanisms of primary differentiation (i.e. Magma Ocean).
- Duration of primary differentiation.
- Origin of the earliest crust.
- Mechanisms of core formation.

Relevance to Mars Science

- Characterize mechanisms of the martian primary differentiation event and its influence on further evolution.
- Characterize the nature and origin of the primary martian crust.
- Determine relation of crust formation and surface manifestations of the martian magnetic field.

Possible Lunar Measurements

- Seismic network to understand the deep and shallow structure of the Moon.
- Ages & geochemistry of farside lunar highlands rocks
- Sample analyses of the deep lunar crust at large impact craters/basins

A3. Thermal and Magmatic Evolution

What is the Linkage?

- Deciphering the thermal and magmatic evolution is fundamental to understanding the dynamics of planetary interiors and the expression of mantle processes on a planet's surface.
- Thermal and magmatic processes may have provided energy and suitable habitats for life.

Relevance to Lunar Science

- Dynamics of the lunar interior and changes in those processes with time.
- Nature and location of basalt sources with time.
- Variation of magma production rate versus time.
- History of crust and lithosphere growth.

Relevance to Mars Science

- Evaluate igneous processes and evolution through time.
- Evaluate the extent, level, locations and persistence of geothermal heat that might have supported a subsurface biosphere.
- Determine vertical structure, chemical and mineralogical composition of the crust and its variations.

Possible Lunar Measurements

- Heat flow outside the PKT.
- Distribution, composition and age of basalts that predate basin formation and that represent the last stages of mare volcanism.
- Distribution of heat-producing elements.
- Mineralogic & isotopic analysis of samples outside the PKT

A4. Planetary Asymmetry

What is the Linkage?

- Mars exhibits a north-south hemispheric dichotomy and Moon exhibits a nearside/farside asymmetry. Lunar geochemistry is also asymmetric.
- In both cases, asymmetry is related to early differentiation/convection or bombardment history, and likely played a key role in subsequent thermal and magmatic evolution.

Relevance to Lunar Science

- Mechanisms of early global differentiation. Distribution of magma ocean products.
- Segregation of KREEP.
- Role of late accreting large impactors in modifying crust.

Relevance to Mars Science

- Characterize post-accretion differentiation, including the role of a magma ocean.
- Determine the origin and history of southern highlands & northern lowlands.
- Examine early convection and plate tectonics, and their effects on subsequent thermal and volcanic history.
- Establish the potential role of late accreting large impactors.

Possible Lunar Measurements

- Geophysics (gravity, seismology, topography) for crustal thickness and paleo-heat flow, especially lunar farside.
- Geochemistry (global and in-situ) to determine crustal compositions and lateral & vertical variability.
- Heat flow (multiple distributed locations) to determine distribution of heat sources with location and depth.

A5. Impactor Flux vs. Time

What is the Linkage?

- Planetary surfaces in the inner solar system bombarded by a common population of impactors.
- Understanding lunar impact history tells us about terrestrial and martian impact history.
- First ~1 Gyr is pivotal to understanding early planetary evolution and the origin of life. Later, large terrestrial impacts have environmental consequences.

Relevance to Lunar Science

- Determine nature of terminal lunar bombardment.
- Constrain cratering rate, provide absolute timing for lunar events.
- Time period over which large impact basins and highlands formed.
- Determine composition of early impactors.

Relevance to Mars Science

- Constrain martian cratering rate, provide absolute timing of martian events.
- Establish the duration of formation of large impact basins and highlands.
- Examine the effects of the impact flux on environments necessary for the development of life.

Possible Lunar Measurements

- Determine ages of impact craters and basins.
- Radiometric ages of melts, exposure age of ejecta.
- Radiometric age of lava flows with well-documented crater density.
- Determine trace element composition in impact melts.

A6. Regolith History

What is the Linkage?

- Mars and Moon covered by regolith of physically comminuted and chemically altered materials.
- Regolith records environmental history.
- Regolith may contain mineral and/or volatile resources.

Relevance to Lunar Science

- Understand regolith formation and mixing processes.
- Understand time scale and rates of regolith formation.
- Understand regolith depth and rock population in areas targeted for resource extraction.

Relevance to Mars Science

- Understand mechanical regolith formation processes and time scales.
- Determine near-surface exposure and mixing history using tracers of cosmic particle interactions.
- Understand chemical alteration processes and time scales.

Possible Lunar Measurements

- Orbital sounding radar.
- Surface ground penetrating radar, seismic reflection / refraction or electrical methods.
- Shallow drilling.
- Understand alteration from exposure to space environment.

A7. Energetic Particle History

What is the Linkage?

- Inner solar system bodies irradiated over time by similar populations of energetic charged particles (solar and cosmic).
- Fossil regoliths and breccias on the Moon and Mars may contain records of those populations.

Relevance to Lunar Science

- Characterize early solar wind composition and distinguish those species from lunar species.
- Characterize intensity of early solar and cosmic irradiation.

Relevance to Mars Science

- Characterize the role of energetic particle irradiation in atmospheric evolution and loss processes.
- Determine whether and which martian volatile compositions began at solar levels.

Possible Lunar Measurements

- Composition of solar wind and flares in fossil regoliths.
- Composition of cosmic radiation induced and implanted species.
- Develop techniques to access regoliths.

A8. Endogenic Volatiles

What is the Linkage?

- Moon is largely volatile depleted; Mars enriched.
- Sampled minerals, gases released from lunar interior water poor.
- Minerals, gases released from martian interior could be more water-rich.

Relevance to Lunar Science

- Understand volatile amount and composition released from interior.
- Characterize depth of origin of volatile species.
- Understand volatile loss processes.

Relevance to Mars Science

- Characterize exogenous and endogenous volatile component on Mars.
- Origin and evolution of martian atmosphere.
- Evolution of surface volatile composition through time.

Possible Lunar Measurements

- Characterize polar volatiles; identify endogenic species.
- Characterize pyroclastic deposits.
- Study composition, depths of origin of surficial volatile species

A9. Exogenous Volatiles

What is the Linkage?

- Both Moon and Mars experienced asteroid and comet bombardment.
- Both provide a variety of volatiles (e.g., water, organics).
- Late stage cometary flux may be the source of crustal volatiles.

Relevance to Lunar Science

- Characterize polar volatiles, especially water, as possible resource.
- Understand volatile transport on airless body.

Relevance to Mars Science

- Establish the importance of exogenous input as source of water and organics, and their relevance for pre-biotic chemistry.
- Determine the origin and evolution of the martian atmosphere.
- Examine the evolution of surface volatile composition through time.

Possible Lunar Measurements

- Characterize polar volatiles; identify exogenous species.
- Determine stratigraphic relationships of volatile deposits.

A10. Interpreting Geologic Environments

What is the Linkage?

- Determining how materials found at the planet's surface formed is key to understanding past and present geologic environments.
- Rock and mineral compositions are tracers of geologic processes.
- Links on-surface measurements to orbital science and to field geology.

Relevance to Lunar Science

- Determine types, provenance, and origin of rock fragments and soils, and relate them to specific geologic formations or settings.
- Establish global distribution of rock types to evaluate crust formation and modification scenarios.

Relevance to Mars Science

- Determine past & present geologic and environmental conditions including chemical weathering.
- Identify mineral hosts for bio-logically important C-H-O-N-P-S group of elements.
- Identify & determine distribution of hydrous & hydrothermal minerals.

Possible Lunar Measurements

- On-surface, in-situ mineralogical analysis from fixed or mobile platforms.
- On-surface remote sensing (stand-off analytical methods from fixed or mobile platforms).
- Orbital measurements with high mineral specificity/spatial resolution.

Category B.

Evaluate lunar resources to be used to support exploration activities on the Moon and beyond.

Critical Resources:

- H and O (both as water and elementally).
- Regolith.
- CH_4
- Metals

Objectives:

- Identification, concentration, distribution.
- Characterization of mining properties.
- Demonstration of use.

B1. Water as a Resource

What is the Linkage?

- Water is critical to life support for human missions to both bodies.
- Moon and Mars may contain accessible water in various forms.
- Exploration questions are similar: What is form, concentration, extraction processes.

Relevance to Lunar Exploration

- Determine locations and physical/ chemical form of lunar water
- Utilize water-rich layers as tracers for lunar regolith processes.
- Utilize lunar propellant to support Moon-space transportation.

Relevance to Mars Exploration

- Demonstrate use of in situ derived water for life support activities.
- Develop/demonstrate exploration approaches to determining chemical and physical properties of volatile deposits.

Possible Lunar Measurements

- Characterize of hydrogen in lunar polar regions – form, concentration, extractability.
- Develop efficient technologies for excavating regolith and extracting H_2/H_2O.
- Develop technologies for purification and storage.

B2. In-situ fuel sources

What is the Linkage?

- Propellant production from lunar resources reduces the fuel mass launched from Earth for lunar and martian flights.
- Energy needed from the Moon to LEO is less than from the Earth's surface to LEO.
- Potentially similar extraction techniques for regolith-bound water.

Relevance to Lunar Exploration

- Provides fuel for transfer from LEO to Moon or Mars.
- Lunar surface operations.

Relevance to Mars Exploration

- Propellant production.
- Demonstrate H / O production from H_2O. Possibly demonstrate CH_4 production.
- Demonstrate the use of in-situ resources in fuel cells or as propellant for surface vehicle engines.

Possible Lunar Measurements

- Relevant propellants are H, O, CH_4, SiH_4.
  - C, H distribution in lunar soil.
  - H_2O content in polar ice.
- Excavation and extraction technology demonstrations.

B3. Exploration and Processing of Planetary Materials

What is the Linkage?

- Demonstration of viability of in situ resources on Moon can validate their use on Mars.
- Non-volatile materials can be manufactured from natural oxides and silicates.
- Processing systems must operate in similar environments – low ambient pressure, partial – g.

Relevance to Lunar Exploration

- Wide variety of products can be made from regolith – glass, ceramics, composites.
- Exploration for the distribution of resources from orbit and with new techniques on surface is needed.

Relevance to Mars Exploration

- Surface techniques needed to establish mineralogy of martian resource materials (e.g. X-ray diffraction; differential thermal analysis).
- Wide variety of products can be made from regolith – glass, ceramics, composites.

Possible Lunar Measurements

- Distribution of significant potential resources established through regolith studies.
- Extraction of minor / trace constituents from lunar regolith through physical beneficiation and chemical extraction.
- Demonstration of manufacturing.

Category C.

Demonstrations at the Moon to gain experience, mitigate risk, improve performance, confirm capability.

- Scientific instruments and experiments.
- Tools (e.g., sample acquisition, manipulation).
- Exploration strategies and operations.
- Long-term surface operations.
- Autonomous and controlled robotic operations (e.g., telepresence).
- Resource extraction (e.g., regolith processing).

C1. In-situ Sample Selection and Analysis

What is the Linkage?

- Chemical, mineral and physical characterization of selected surface samples is a major element of the scientific study of both Moon and Mars.
- Many to most rocks collected near the surface of both Moon and Mars are regolith fragments and can only be analyzed after separation from the regolith
- Robotic missions may demonstrate laboratory instrumentation that will be included in human exploration missions

Relevance to Lunar Science

- Basic chemical, mineral, and physical data will be needed for resource characterization and for any experiment that requires pre-selection from a large number of similar rock fragments
- On-site instruments will increase the effectiveness of human explorers
- Techniques for rapidly screening large numbers of regolith rock fragments can enable new lunar science investigations

Relevance to Mars Science

- In-situ chemical, mineral, and physical characterization of rocks and regolith is an important tool in surface exploration
- Information on the distribution of compositions of rocks gained from in-situ analyses will improve interpretability of global remote sensing data and allow extrapolation from sample return data.

Possible Lunar Measurements

- Develop robotic instrumentation to determine approximate ages of rocks
- Develop robotic instrumentation to measure basic chemical and mineralogical character of small rock fragments from the regolith
- Develop and test techniques to rapidly screen samples for return to Earth by human missions

C2. Communication and Ranging Systems

What is the Linkage?

- Continuous communication with landers and sensor networks provides a planetary "virtual presence" for robotic explorers and demonstrates emerging laser & high-rate radar technology for Telecom Orbiters
- Stable lunar geodetic baseline facilitates tests for existence of liquid cores and tests of general relativity at solar system scale.

Relevance to Lunar Science

- Continuous monitoring on lunar farside (SP-Aitken) and sunlit poles
- Precision targeting and navigation
- Closed-loop remote robotic operation
- Measurement of forced librations and thereby internal structure
- Gravity mapping, particularly lunar farside

Relevance to Mars Science

- Higher-rate mission data return
- Measurement of variations in length of day
- Characterization of seasonal and interannual mass transfer between lithosphere and atmosphere
- Rotational dynamics of the Martian core
- Improved gravity maps

Possible Lunar Measurements

- Seismic and electromagnetic networks
- Moon-satellite-earth tracking and gravity measurement via geodetic S/C
- Laser ranging to lander cornercubes
- VLBI tracking of lunar transponders
- Precision laser ranging to Mars transponders

C3. Drilling Technologies

What is the Linkage?

- Subsurface access, for the purpose of controlled scientific access, is important at both Mars and the Moon.
- Technologies relevant both to robotic and human missions.
- Drilling is the preferred approach for "deep" subsurface access.

Relevance to Lunar Science

- Drilling is important as it allows the subsurface stratigraphy to be carefully sampled. The stratigraphy holds the records of volatile influx (e.g., at the poles) or solar flux as a function of time (paleoregoliths).

Relevance to Mars Science

- Enable examination of possible hospitable environment for life on Mars (i.e. the subsurface).
- Develop access to subsurface aquifers for sampling for both science and resources.
- Improve performance of geophysical sensors with subsurface access.

Possible Lunar Measurements

- Shallow (<10 m) Volatiles.
- "Deep" (10-50 m) Regolith stratigraphy.
- "Very deep" (>100 m) Sampling of the in situ lunar crust.

C4. Seismic Technologies/Studies

What is the Linkage?

- Understanding the interior structure, is important at both Mars and the Moon.
- Technologies relevant both to robotic and human missions.
- A seismic network is required to understand the inner workings of any solid planetary body.

Relevance to Lunar Science

- The Apollo program deployed 4 seismometers, but all were on the near-side and relatively close to each other.
- The structure and composition of the lunar deep interior is still unknown as is the crustal structure on the far-side.

Relevance to Mars Science

- Insights into deploying a robust seismic network on Mars.
- Evidence of continuing tectonic and magmatic activity.
- Understanding the internal structure and composition of Mars.
- Characterization of the shallow subsurface in some regions (e.g., extent of potential aquifiers).

Possible Lunar Measurements

- Define the nature and composition of the lunar interior.
- Characterization of the depth of regolith in some regions.
- Define crustal/mantle heterogeneity.
- Define the composition and size of the lunar core.
- Test the lunar magma ocean hypothesis.

C5. Assess Bio-Organic Contamination

What is the Linkage?

- The Moon is the most accessible sterile planetary environment. Therefore, the extent and character of contamination by terrestrial microbes and organic molecules carried by robotic and human explorers can be assessed during lunar exploration missions.

Relevance to Lunar Science

- None

Relevance to Mars Science

- Quantification and characterization of contamination would minimize "false positives" or ambiguous results in investigations of extant life, extinct life or organic precursor compounds on Mars.
- Determine the differences in the signature of contamination for robotic vs. human missions.
- Contamination data could aid in development of policies to minimize environmental impact of Mars exploration and of sample return to Earth.

Possible Lunar Measurements

- Quantify and characterize organics, microbial residues and any surviving organisms on and around spacecraft and astronauts on the lunar surface.
- Conduct control experiments of instruments designed to detect extant or extinct life or precursor compounds.
- Test technologies and protocols intended to minimize bio-organic contamination of planetary environments, particularly by human explorers.

C6. ISRU Technology Demonstrations

What is the Linkage?

- Use of in-situ resources for support of human and robotic missions.
- Although there is significant differences in the surface environments that could lead to different technological approaches, at a sub-system level, there are many commonalities.
- Many processes are affected by operations at reduced gravity levels (two phase flows, scaling laws for material handling).
- Demonstrating reliability/stability/longevity of power systems and sensors in a harsh planetary environment

Relevance to Lunar Science

- Excavation technologies (and knowledge of regolith physical properties) are required for any process that extracts useful materials from the regolith (e.g. radiation shielding, oxygen production)
- Efficient thermal extraction processes needed to demonstrate feasibility of extracting minor volatile constituents from regolith (H, C, N)
- Materials handling (both solids and gases) demonstrations are needed to understand factors that will allow scale-up from robotic to human scale missions.

Relevance to Mars Science

- Excavation technologies are required for any process that extracts useful materials from the regolith (e.g. radiation shielding, water extraction from hydrated minerals) on Mars.
- Demonstration of ISRU capability on the Moon will increase the likelihood that such approaches will be used on Mars.
- Long-term testing of systems to establish reliability and maintainability is essential because Mars applications will be difficult to repair if they fail.

Possible Lunar Measurements

- Practical small-scale excavators.
- Regolith thermal extraction of volatiles and gas separation and purification technologies.
- Hydrogen or carbon reduction processing of lunar regolith to produce oxygen.
- Demonstrations of practical use for lunar exploration, such as charging a fuel cell on a rover for long-range exploration.

C7. Sample Return

What is the Linkage?

- Sample return is a key approach for exploring both Mars and Moon.
- Sample return missions allow the full range of terrestrial analytical techniques to be used to address important planetary problems.
- Future lunar missions to sample geologically complex materials will be directly relevant to sample acquisition and return from Mars.

Relevance to Lunar Science

- Lunar sample return missions have been conducted by robotic and human means, but all were restricted to the lunar equator on the near-side.
- Additional sample return missions can be designed to address high-priority planetary science issues.

Relevance to Mars Science

- MSR missions can be conducted with currently known technologies, but technical feasibility of MSR can be advanced based on the lunar experience.
- Search for evidence of life.
- Define the nature and history of the martian crust and mantle.

Possible Lunar Measurements

- Define the variability in materials and composition of the lunar crust.
- Define the impact chronology of the inner solar system.
- Test the lunar magma ocean hypothesis.
- Decipher processes for trapping of volatiles at the poles.

Moon→Mars Priorities

<u>FINDING</u>: We have found significant differences in the **<u>relative</u>** priority of the identified Moon→Mars linkages.

1. The priority of Moon→Mars linkages was assessed:
   a) From the perspective of Mars alone
   b) From the perspective of the Moon alone

Results are shown in the following tables.

<u>Note</u>: Assessing priority in an absolute sense requires that factors beyond the scope of this study be considered.

Priority of Identified Lunar Investigations
to Mars Science

RELATIVE PRIORITY

HIGHER

PRIORITY GROUP 1:

A5: Impactor Flux vs. Time

A9: Exogenous Volatiles

PRIORITY GROUP 2:

A3: Thermal and Magmatic Evolution

A10: Interpreting Geologic Environments

A6: Regolith History

A8: Endogenous Volatiles

PRIORITY GROUP 3:

A1: Interior Planetary Structure

A4: Planetary Asymmetry

A2: Early Planetary Differentiation

A7: Energetic Particle History

LOWER

Prioritization Criteria:

- The intrinsic scientific value of each theme for advancing our understanding of Mars if the investigation was first carried out on the Moon.
- Degree of criticality of the possible lunar activity to one or more future Mars missions (or surface measurement activities)
- Degree of alignment with MEPAG's priority system for Mars exploration

Note: Differences in priority within priority groups are not judged to be significant.

Priority of Identified Lunar Investigations
to Lunar Science

RELATIVE PRIORITY

HIGHER

PRIORITY GROUP 1:

A1. Interior Planetary Structure

A2. Early Planetary Differentiation

A5. Impactor Flux vs. Time

PRIORITY GROUP 2:

A3. Thermal & Magmatic Evolution

A4. Planetary Asymmetry

A10. Interpreting Geologic Environments

A9. Exogeneous Volatiles

A6. Regolith History

PRIORITY GROUP 3:

A7. Energetic Particle History

A8. Endogenic Volatiles

LOWER

Prioritization Criteria:

- Intrinsic scientific value (for the Moon).
- Degree to which identified investigations are likely to make major contributions to advancing knowledge about the important science questions.
- Feasibility within the emerging strategy for precursor robotic lunar missions in support of human exploration.

Note: Differences in priority within priority groups are not judged to be significant.

Priority of Identified Lunar Investigations

Summary Comparison

A2. Early Planetary Differentiation A1. Interior Planetary Structure		A5. Impactor Flux vs. Time
A4. Planetary Asymmetry	A6. Regolith Hist. A10. Interpreting Geologic Environments	A9. Exogeneous Volatiles
A7. Energetic Particle History	A8. Endogenic Volatiles	

Vertical axis (from top to bottom): *HIGHER* — *RELATIVE PRIORITY* — *LOWER*, labeled **TO LUNAR SCIENCE**

Horizontal axis (from left to right): *LOWER* — *RELATIVE PRIORITY* — *HIGHER*, labeled **TO MARTIAN SCIENCE**

Resource and Demo. Priorities

Test crucial instrument or strategy, or establish test bed under the proviso that (*i*) Activity cannot be done satisfactorily on Earth, or (*ii*) Moon provides a unique (or vastly superior) martian analog than does the Earth.

RELATIVE PRIORITY

HIGHER

PRIORITY GROUP #1:

C1: In-situ sample selection and analysis
C7: Sample Return
C3: Drilling technologies

PRIORITY GROUP #2:

C4: Seismic technologies/Studies
B1: Water as a Resource
B2: In-situ fuel resources
C5: Assess Bio-Organic Contamination

PRIORITY GROUP #3:

C6: ISRU Technology Demonstrations
C2: Communication and ranging systems
B3: Other resource issues

LOWER

Prioritization Criteria:

1. If successfully carried out at the Moon, the value to our ability to correctly plan and successfully implement the future Mars exploration program.
2. Timing: Importance that these measurements/demonstrations be carried out by the lunar robotic program prior to 2020.
3. Cost: General affordability of these measurements/ demonstrations.
4. Technology readiness: Our technical ability to carry out these measurements/ demonstrations within the time frame specified in #2 above.

Summary of Priority Findings

FINDING: The following possible lunar investigations/ demonstrations are of relatively high priority to martian science objectives.

Highest Relative Priority		
A5	Impactor Flux vs. Time	**Of general value**
A9	Exogenous Volatiles	**Of general value**
High Relative Priority		
A6	Regolith History	**Of general value**
A10	Interpreting Geologic Environments	**Of general value**
A3	Thermal and Magmatic Evolution	**Of general value**
A8	Endogenic Volatiles	**Of general value**
C1	In-situ sample selection and analysis	**Of general value, but of particular value if done 4 years before AFL**
C7	Sample Return	**Valuable if done 4 years before MSR**
C3	Drilling technologies	**Valuable if done before "Deep Drill" (robotic) or before human mission with drilling objectives**